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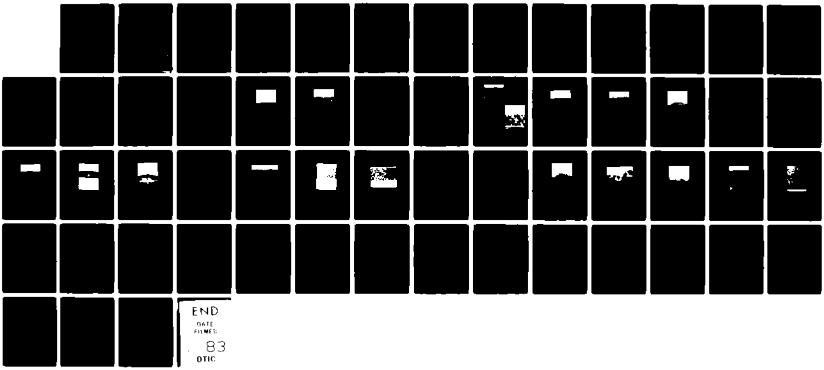

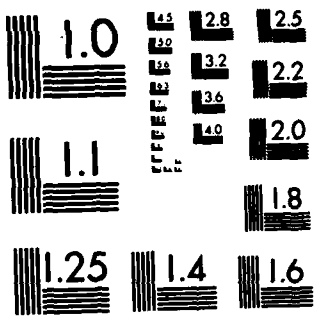

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LASER DENSIFICATION OF PLASMA SPRAYED REFRACTORY METAL COATINGS ON 4340 STEEL

DECEMBER 1982

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FINAL REPORT

Contract No. DAAG46-80-C-0044

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This program investigated the feasibility of surface melting and densification of plasma sprayed refractory metal coatings on SAE 4340 steel by means of a 15 kW CO_2 laser. The refractory metals and alloys investigated were: Tantalum, TA-10W, Molybdenum and the Columbium base alloys WC 103 and WC 3015.

True cladding, by melting of the plasma sprayed coatings, could not be achieved without damage to the substrate, or without alloying with the substrate. Partial melting or densification could be obtained, but pore formation and contamination by oxygen and nitrogen from the ambient atmosphere occurred in nearly all cases. It may, however, be possible to overcome these problems by improving the protective atmosphere used for the processing; and by laser processing the refractory metals in the form of loose powder on the substrate surface rather than as a plasma sprayed layer.

Cladding of SAE 4340 steel with Stellite No. 12 was also investigated. Good, fully dense continuous layers, ~ 0.07 in. thick, with a hardness of R_c 48-50, were obtained.

FOREWORD

This report describes experimental work on laser densification of plasma sprayed refractory metal coatings on SAE 4340 steel substrates with Stellite No. 12 alloy.

The work was performed under Contract DAAG-46-80-C-0044, awarded by Army Materials and Mechanics Research Center (AMMRC) to Avco Everett Research Laboratory, Inc., (AERL) on 17 June 1980.

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1.0 INTRODUCTION

The erosion of the bore of large gun barrels, due to repeated firings, is an important factor in limiting the performance and useful life of such guns. In particular, the erosion at the origin of rifling can cause the gun barrel to become unserviceable long before its fatigue life is realized.[1] This erosion is thought to result from the extreme temperatures and high stresses experienced by the bore surface during firing. Under certain circumstances, localized surface melting may occur. This, in combination with the very high stresses caused by the movement of the projectile up the barrel, can result in severe damage to the bore surface particularly at the origin of rifling.

To reduce the erosion in this area, chrome plating is frequently applied to the bore surface to enhance erosion resistance. The high melting point (1875°C) and good thermal conductivity of chromium will also tend to prevent surface melting. However, the brittleness and crack susceptibility of electroplated chromium is a serious problem.

In order to study the potential benefits of protecting the critical area of the bore surface with other high melting or erosion resistant materials, work was undertaken to investigate the feasibility of using large, industrial lasers to melt or densify layers of plasma sprayed refractory metals and alloys on SAE 4340 steel substrates. Since the laser can deliver very high intensity energy fluxes to a workpiece, it was hoped that it would be possible to obtain melting or substantial densification of the plasma sprayed material without damage to the substrate, even in cases where the melting point of the plasma sprayed material was much higher than that of the substrate.

The metals and alloys selected for this study were Tantalum, Tantalum-10 Tungsten, Molybdenum and the Cb base alloys WC 103 and WC 3015 (see Table 1). These alloys were selected in order to give a range of melting points from a high of 2995°C for Tantalum to ~ 2300°C for WC 103 and WC 3105. Pure Columbium metal was not included in this study, because laser processing of plasma sprayed Cb had been investigated in an earlier program.[2] In that investigation, it was shown to be possible to obtain densification of plasma sprayed Columbium on SAE 4340 substrates, but complete melting of the Cb-layer could not be achieved without damage to the substrate. Laser processing of electroplated chromium on SAE 4340 samples, for the purpose of consolidation, surface melting and substrate hardening had also been performed earlier.[3] It was found that chrome plated steel could be laser hardened, but blistering and softening of the chromium took place.

Chromium was therefore not considered in this work. However, it was decided to include a lower melting commercial hard-facing alloy with good high temperature hardness and erosion resistance. Stellite No. 12 (see Table 1) was selected for this purpose.

TABLE 1. COMPOSITION OF MATERIAL

MATERIAL	WEIGHT %														
Mo	Mo														
	99+														
Ta	W	Cb	Fe	Ni	Mo	Ti	Zr	C	O	TA					
	0.93	0.042	0.005	0.001	0.017	0.001	0.025	0.0038	0.088	Bal					
Ta-10W	W	Cb	Fe	Ni	Mo	Ti	Zr	Si	Co	N	Ta				
	10.6	0.098	0.0035	0.002	0.002	0.002	0.002	0.0067	0.079	0.004	Bal				
WC-3015	Ti	Zr	Hf	C	W	Ta	Fe	Mo	Al	Si	B	O	H	N	Cb
	4.5	1	26.7	0.3	10.9	1.7	0.0265	0.02	<0.002	0.0106	$<10^{-4}$	0.162	0.013	0.183	Bal
WC-103	Ti	Zr	Hf	C	W	Ta	Fe	Mo	Al	Si	B	O	H	N	Cb
	1	0.7	10	0.062	10.9	1.7	0.0265	0.02	<0.002	0.0106	$<10^{-4}$	0.162	0.013	0.183	Bal
Stellite #12	W	Cr	C	Co											
	9	29	1.8	Bal											

Originally, tungsten was also included in this study program, but the very high melting point of tungsten (3410°C), which is even higher than the boiling point of the steel substrate material (~ 3000°C), would have made it impossible to obtain laser cladding by melting or densification of plasma sprayed tungsten without collapse of the SAE 4340 steel substrate.

2.0 DISCUSSION

2.1 MATERIALS AND SAMPLE PREPARATION

The compositions of the six materials studies in this program are listed in Table 1. The specimens for laser processing were prepared by plasma spraying these materials on hardened (Rc54) SAE 4340 steel substrates measuring 4 in. x 4 in. x 1/2 in. The specimen preparation was performed by AMMRC, using a Metco type 3MB plasma flame spray gun. The details of the preparation procedure are summarized in Table 2.

2.2 EXPERIMENTAL EQUIPMENT AND PROCEDURES

All laser processing described in this report was performed on an Avco HPL® 15 kW, CO_2 laser with cw output. A focused laser beam with a nominal diameter of 0.05 in. (0.127 cm) in the focal plane was used for processing the samples. This spot was scanned back and forth in a direction normal to the processing direction by means of an oscillating copper mirror. The frequency of oscillation was 42 Hz and the amplitude could be varied from ± 0.5 in. (1.27 cm) to ± 0.25 in. (0.635 cm). In this manner, a rectangular laser spot with length 0.05 in. (0.127 cm) in the processing direction and a width equal to the amplitude of oscillation could be generated in the focal plane.

The specimens were mounted on a motor driven slide inside a metal enclosure as shown in Figure 1. This enclosure was evacuated prior to laser processing by means of a rotary vacuum pump, and backfilled with welding grade argon gas. The laser beam entrance port on top of the enclosure was closed during evacuation and opened just prior to start of processing. In order to reduce the influx of air into the enclosure, the argon gas atmosphere was kept streaming to the enclosure at a slight overpressure.

The specimens were laser processed by moving them at a preset speed under the stationary laser beam. In this way, a strip of laser processed material across the specimen, equal to the width of the beam, could be obtained. Each such traverse is here referred to as a laser run and given a number designation.

After each run, the specimen was allowed to cool, and the enclosure was then re-evacuated and backfilled with fresh argon gas before the next run. Several runs could be made on each specimen for the purpose of determining the most suitable processing parameters.

It would have been more satisfactory to provide the metal enclosure with a vacuum tight window at the laser beam entrance port. However, because the output beam from the CO_2 laser is so easily absorbed in ordinary glasses,

TABLE 2. PLASMA SPRAYING PARAMETERS

MATERIAL	POWDER MESH SIZE	THICKNESS DEPOSIT	SPRAY PARAMETERS AMPS	VOLT	SPRAY DIST.	SPRAY RATE
Mo	-200/+30	0.045"	500	60-70	3" - 5"	9.5 lb/hr
Ta	-120/+200	0.045"	500	60-70	4" - 7"	8 lb/hr
Ta - 10W	-120/+200	0.045"	500	60-70	4" - 7"	8 lb/hr
WC-3015	-200/+325	0.045"	500	60-70	3" - 5"	9.5 lb/hr
WC-103	-200/+325	0.045"	500	60-70	3" - 5"	9.5 lb/hr
STELLITE* #12	-100/+325					

SUBSTRATE: SAE 4340: HARDENED TO R_C 53-55

ATMOSPHERE: ARGON +10% HYDROGEN

* The stellite alloy was introduced to the substrate in the form of loose powder, by means of an automatic powder feeder, during processing.

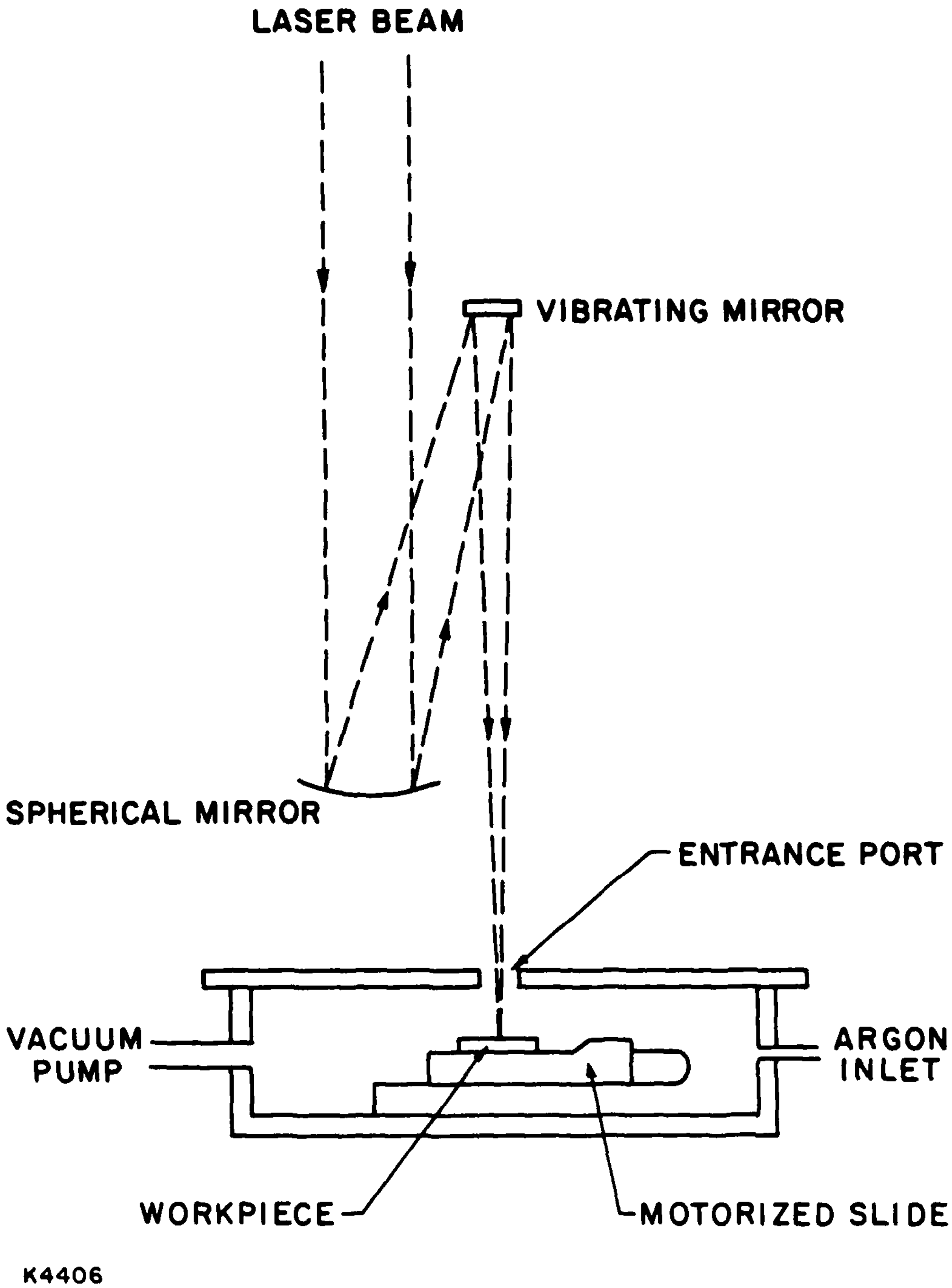

Figure 1. Experimental Arrangement for Refractory Metal Laser Densification

this window must be made from special substances such as potassium chloride (KCℓ), zinc selenide (ZnSe) or gallium arsenide (GaAs), all of which show little absorption of the far infrared radiation generated by the CO_2 laser. An effort was made to use a potassium chloride window at the beam entrance port. However, the high power density of the beam at this point, coupled with indirect heating of the enclosure by the hot specimen and reflected laser radiation invariably resulted in failure of the window by thermal stress cracking.

It was, therefore, necessary to leave the beam entrance port open during laser processing. Contamination by oxygen and nitrogen from the ambient air was unavoidable, but not as severe as if the processing was performed with only an off-axis argon jet for protection of the reaction zone.

The cladding of the SAE 4340 steel samples with Stellite No. 12 was less difficult and was performed with the arrangement shown in Figure 2. In this setup, a 0.5 in. x 0.5 in. (1.27 cm x 1.27 cm) laser spot was generated on the specimen surface by means of an optical integrator. During the initial processing runs with this equipment, plasma sprayed specimens were used, but this proved unsatisfactory resulting in uneven coverage and excessive oxidation. In later work, the Stellite material was applied to the substrate surface in the form of loose powder by means of an automatic powder feeder. This proved much more satisfactory, and thick continuous surface cladding without visible oxide formation could be obtained. In all processing of Stellite, the reaction zone was protected by an off-axis argon jet operated with a flow rate of 12.5 ft^3/hr (103 cm^3/sec).

Metallographic specimens were prepared from the laser processed samples by making cuts normal to the processing direction. The refractory metal specimens were not etched, because the etchtant needed to reveal the structure of these metals, tended to attack the substrate severely.

The Stellite No. 12 cladded samples were etched in Glyceregia (30 cc Glycerol, 25 cc HCℓ, 10 cc HNO_3) followed by immersion in Murakami's etchtant (10 g potassium ferricyanide, 10 g potassium hydroxide in 100 cc water).

Metallographic inspection of the specimens were performed with a Leitz Wetzlar metallograph and microhardness measurements were carried out by means of a Wilson model MO Knoop microhardness tester, using a 500 g load.

Microhardness measurements were made at 0.005 in. intervals from the surface. The observed Knoop hardness values were translated to Rockwell C units by means of standard tables.

2.3 DEVELOPMENT OF PROCESSING PARAMETERS

Prior to start of processing, the actual shape of the laser spot was tested by making short duration burns on lucite blocks. In the case of the arrangement shown in Figure 1, the actual dimension of the spot in the

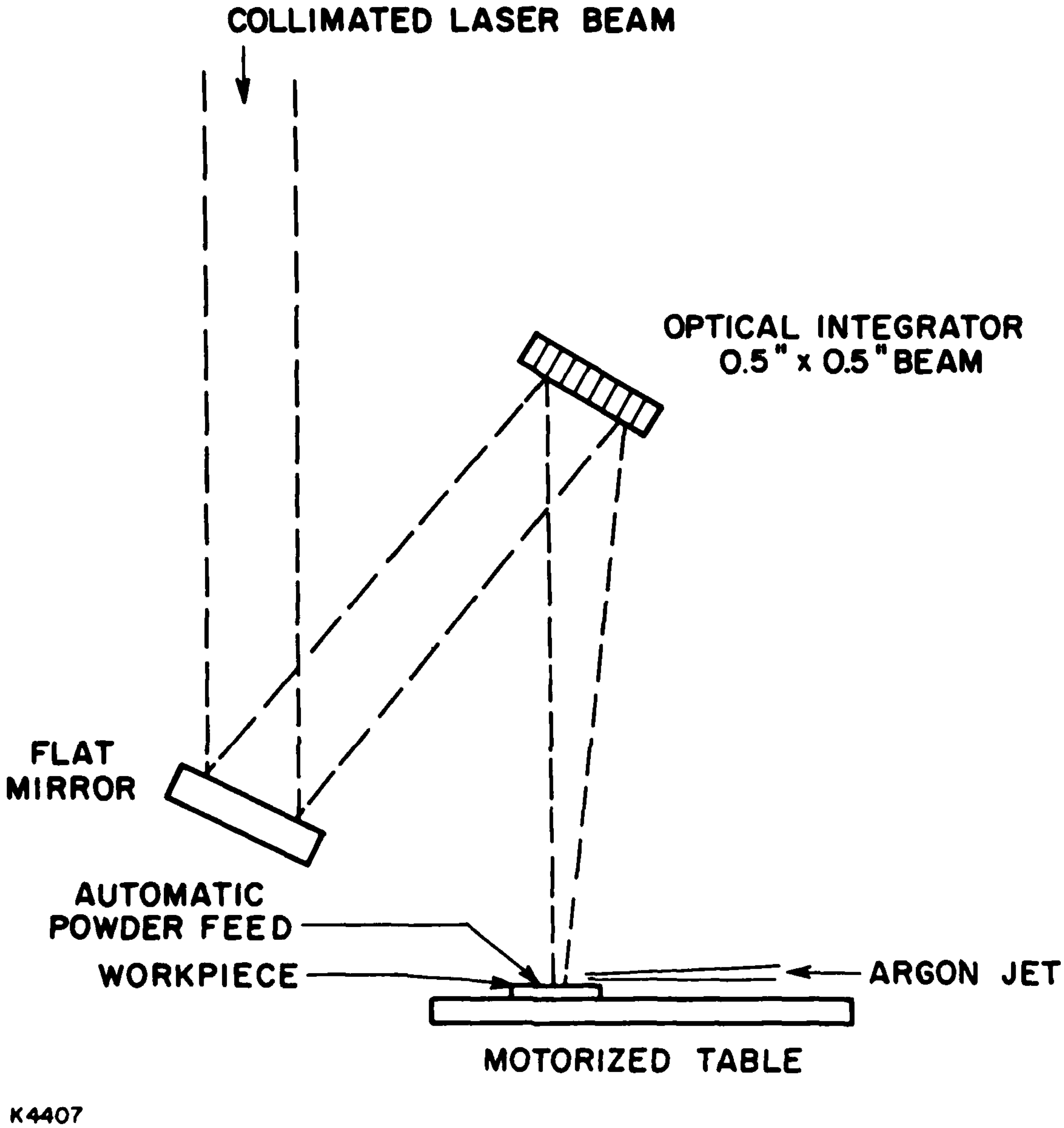

Figure 2. Experimental Arrangement for Laser Cladding of SAE 4340 with Stellite No. 12

processing direction was found to be close to 0.1 in. (0.127 cm) rather than the nominal 0.05 in. (0.064 cm). The maximum power output from the laser was found to be 13.8 kW, but the maximum power delivered to the workpiece measured by calorimetry at that point was found to be 11 kW, the difference being attributed to losses in the beam direction system. With spot size of 0.025 in. x 0.01 in.^{2} [0.161 cm^2] the maximum available power density was therefore 440 kW/in.^{2} (68200 W/cm^2). It was obvious, however, that only a fraction of this power was absorbed in the workpiece, probably < 20 percent (see Appendix).

Molybdenum

A total of 30 test runs were performed at power densities ranging from 168 kW/in.^{2} (26000 W/cm^2) to 440 kW/in.^{2} (68200 W/cm^2). The range of processing speed was from 4 in./min to 35 in./min (0.17 cm/sec to 1.48 cm/sec). The corresponding dwell time, that is, the time a given spot on the surface is exposed to the laser beam was 0.17 to 1.5 sec.

It proved difficult to obtain consistent results, particularly at the higher processing speed. This was apparently caused by variation in laser energy absorption from specimen to specimen and even from one area to another on the same specimen. Pores formed on or near the surface in all runs, and no suitable set of processing parameters could be established. Figure 3 shows the result of fast processing with pore formation at the surface. Note, however, the good bond between coating and substrate. Figure 4 shows extensive pore formation both at or near the surface and at the interface resulting from slow processing. The plasma sprayed layer was often partially separated from the substrate. Cracking and formation of a third phase at the boundary also occurred at slower processing speed, as shown in Figure 5. The hardness profile of this specimen is shown in Figure 6. The reason for the steady increase in hardness of the molybdenum with distance from the surface, is not known but may be linked to the presence of a third phase in the vicinity of the interface, as shown in Figure 5.

Tantalum

A total of 50 test runs were completed on Tantalum. The range of power density was from 168 kW/in.^{2} (26000 W/cm^2) to 440 kW/cm^2 (68200 W/cm^2) at a processing speed range from 6 to 40 in./min 0.25 to 1.69 cm/sec). The corresponding range of dwell time was from 0.15 to 1 sec.

Again, variation of absorptivity was apparent, as was the case with all plasma sprayed material tested in this program. Nevertheless, some densification could be obtained at high power and speed levels as shown in Figures 7 and 8.

At lower power and speed, deep in melting and alloying with the substrate occurred. This is illustrated in Figures 9 and 10. At medium power and speed, considerable melting took place but extensive pore formation also occurred at the melt/solid line as shown in Figure 11. Complete melting of

K6803

Figure 3. Run No. 144 x 18
Mo: 186 kW/in.^{2} 35 in./min

K6803

Figure 4. Run No. 601 x 18
Mo: 184 kW/in.^{2} 12.3 in./min

K6803

Figure 5. Run No. 601 x 180
Mo: 184 kW/in.^{2} 12.3 in./min

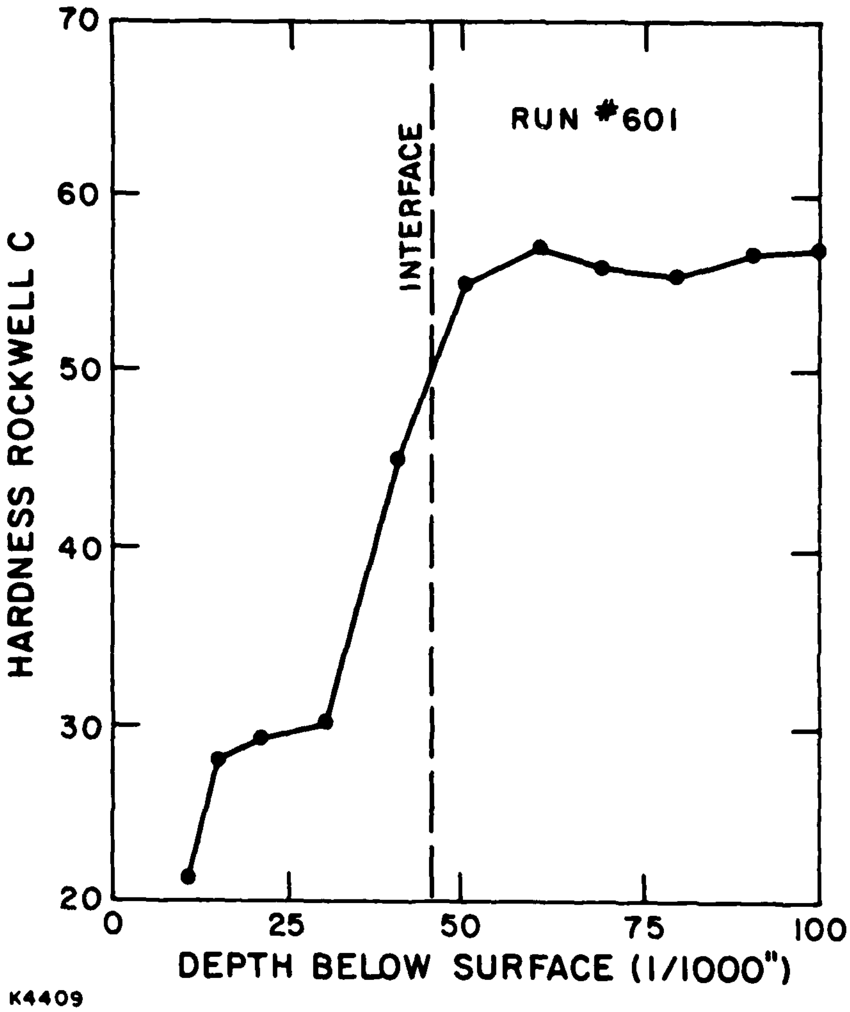

Figure 6. Haraness of Laser Processed Molybdenum on SAE 4340 Steel Substrate

Figure 7. Run No. 229 x 75
Ta: 424 kW/in.^{2}
31.5 in./min

K6804

Figure 8. Unprocessed x 75 Ta

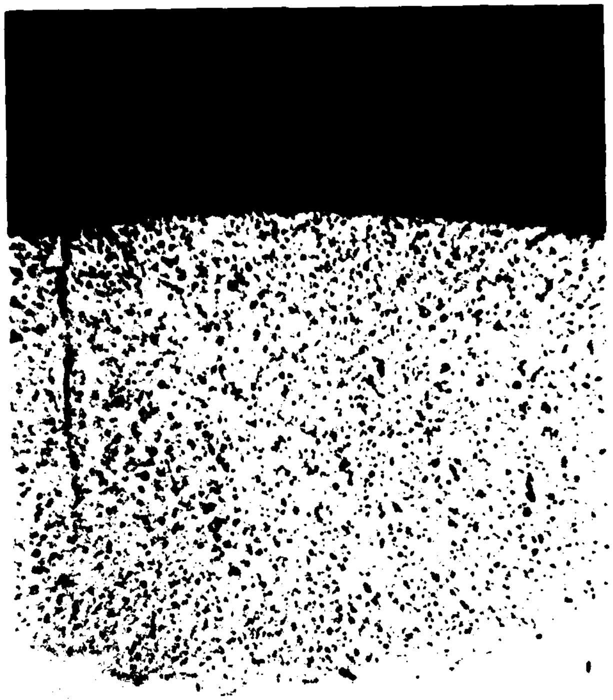

Figure 9. Run No. 158 x 18
Ta: 186 kW/in.^{2} 6 in./min

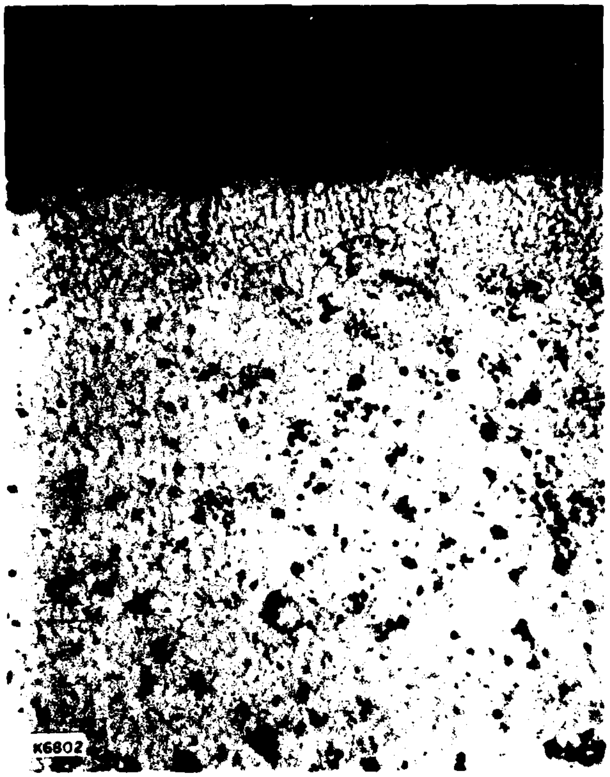

Figure 10. Run No. 158 x 180
Ta: 186 kW/in^2 6 in./min

K6802

Figure 11   Run No. 606 x 18
Ta: 194 kW/in.^{2} 16.8 in./min

the entire plasma sprayed layer could not be achieved without partial melting of the substrate and extensive dilution of the molybdenum by molten substrate material.

The hardness profile obtained on the structure shown in Figure 11 is given in Figure 12. The high hardness of the Tantalum surface layer indicates a high level of impurities, presumably due to contamination by the ambient atmosphere during processing.

Tantalum -10 Tungsten

A total of 37 test runs were made on this material with processing parameters ranging from 110 to 440 kW/in.^{2} (17000 to 68200 W/cm^2) in power density, and with processing speed levels from 9 to 30 in./min (0.38 to 1.27 cm/sec). The range of dwell time was 0.2 to 0.67 sec.

In Tantalum -10 Tungsten, surface melting could be obtained, but again with formation of large pores at the melt-solid interface (see Figures 13 and 14). Processing at lower speed resulted in massive void formation and partial collapse of the substrate surface as shown in Figure 15. The hardness profile obtained on Specimen No. 115 (Figure 14) is shown in Figure 16. Again, the hardness profile indicates a high level of impurities.

WC 103

Fifty test runs were made on WC 103 in order to establish optimum processing parameters. The test parameters ranged from 172 to 440 kW/in.^{2} (42100 to 68200 W/cm^2) for power density, 10 to 45 in./min (0.42 to 1.91 cm/sec) for processing speed, and 0.13 to 0.6 sec for dwell time.

At low processing speed, extensive dilution of the cladding alloy with molten substrate material occurred, as shown in Figure 17. At higher speed the resulting structure was quite porous (see Figure 18). However, considerable densification did occur as indicated in Figure 19, showing laser processed material on the right and unprocessed, plasma sprayed material on the left. Figure 20 shows the hardness profile obtained on this partially densified material. The hardness of the alloy layer is not as high as for Tantalum and Ta-10 W, but some contamination is still indicated by the magnitude of the hardness and its erratic variation from spot to spot. The reason for the low hardness of the substrate in this case is not known, but may be due to tempering of the the hardened material.

WC 3015

About forty test runs were made on WC 3015 with power densities in the range 156 to 432 kW/in.^{2} (24000 to 67000 W/cm^2) and processing speed varying from 20 to 70 in./min (0.82 to 2.96 cm/sec), with corresponding dwell times in the range 0.09 to 0.3 sec.

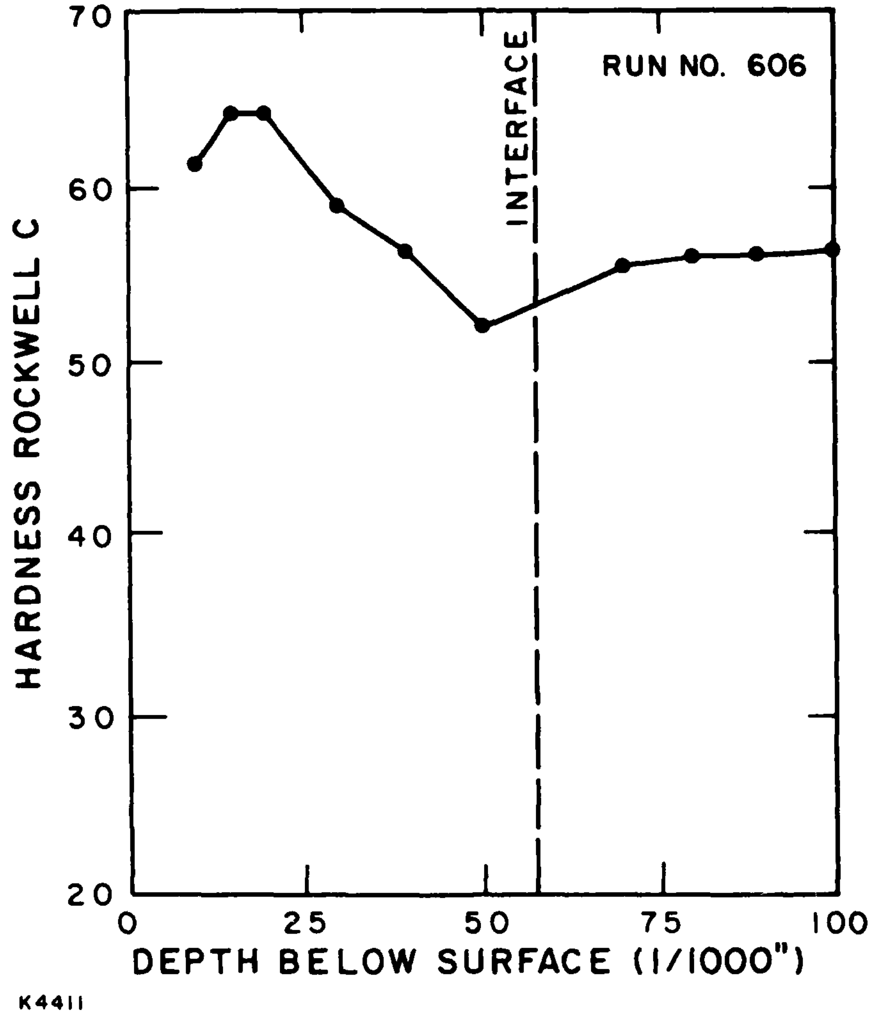

Figure 12. Hardness of Laser Processed Tantalum on SAE 4340 Steel Substrate

Figure 13. Run No. 113 x 18
Ta-10 W: 160 $kW/in.^2$ 15.25 in./min

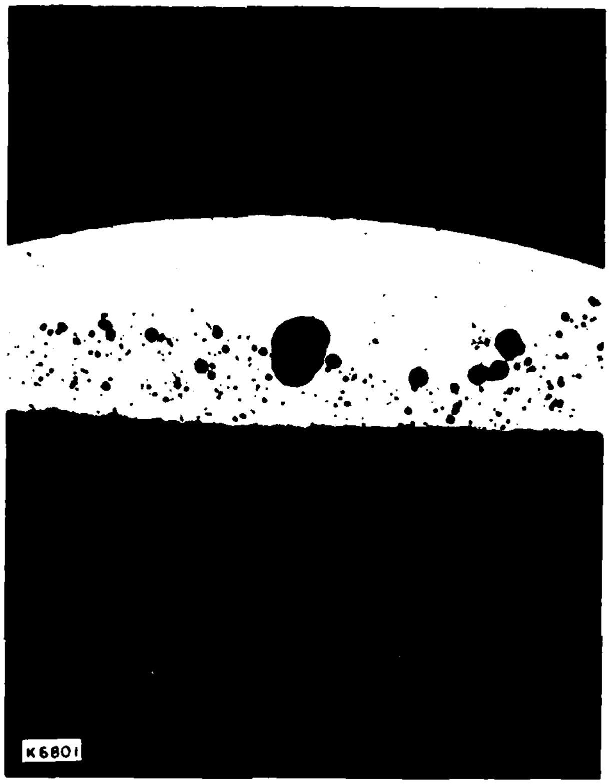

Figure 14. Run No. 115 x 18
Ta-10 W: 198 kW/in.^{2} 16.8 in./min

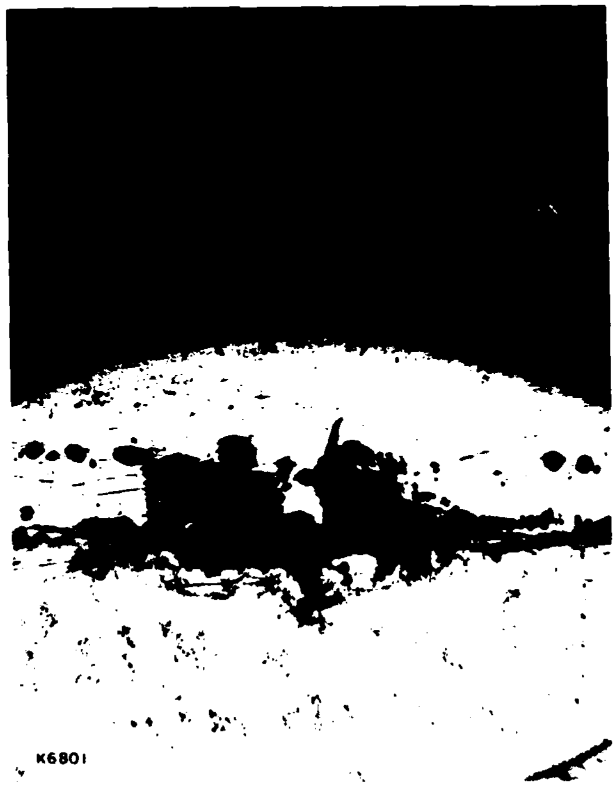

Figure 15. Run No. 622 x 18
Ta-10 W: 220 kW/in.^{2} 12.8 in./min

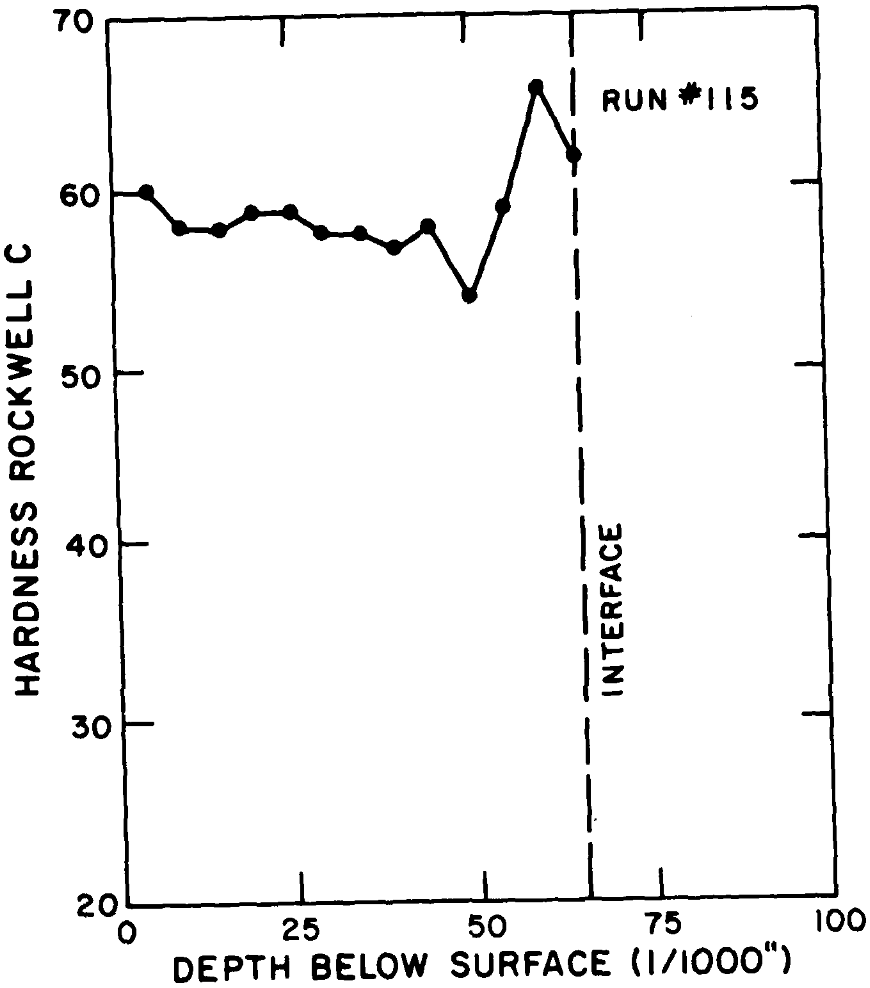

Figure 16. Hardness of Laser Processed Ta-10 W on SAE 4340 Steel Substrate

K6801

Figure 17. Run No. 274 x 18
WC 103: 400 kW/in.^{2} 10.3 in./min

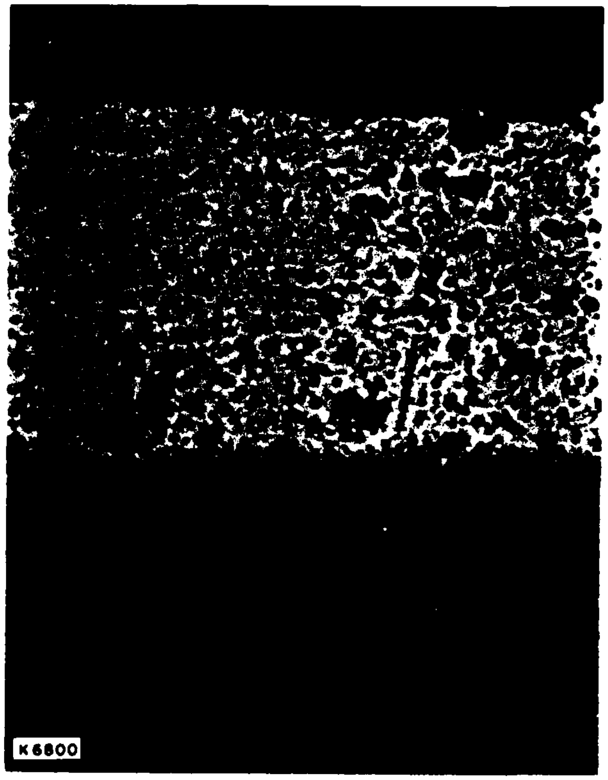

Figure 18. Run No. 352 x 45
WC 103: 187 $kW/in.^2$ 34 in./min

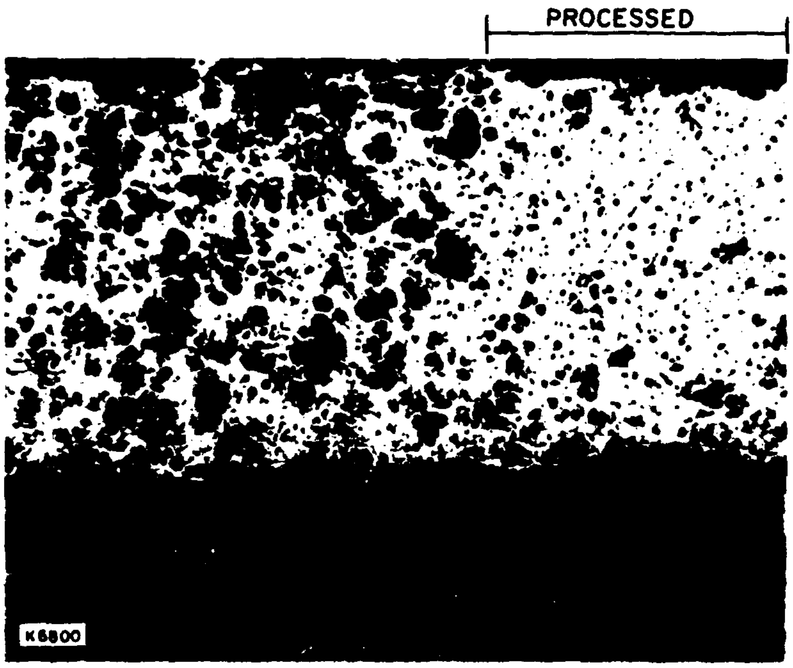

Figure 19. Run No. 352 x 45
WC 103: Left Side: Unprocessed
Right Side: 187 kW/in.^{2}
34 in./min

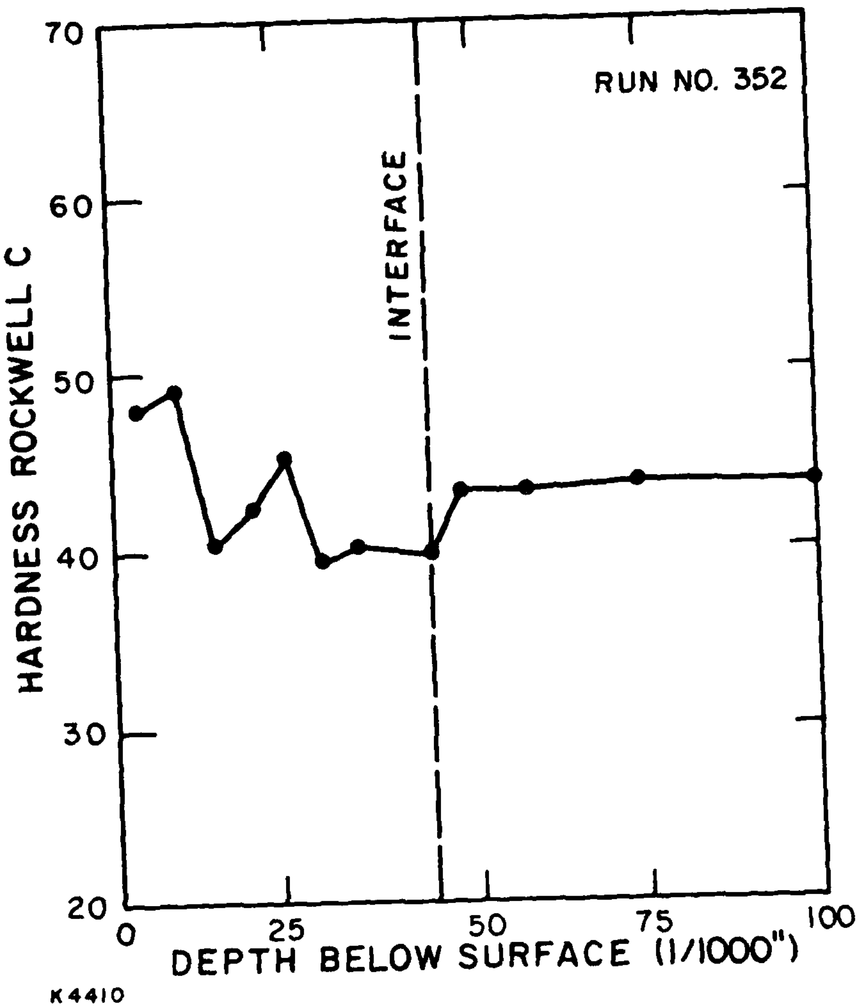

Figure 20. Hardness of Laser Processed WC 103 on SAE 4340 Steel Substrate

At low processing speed, dilution of the cladding alloy with molten substrate occurred, as shown in Figure 21. At higher speed, no power setting could be found that resulted in any visible effect on the plasma sprayed material without damaging the substrate. Breakup of the plasma sprayed material, heavy oxidation and the formation of noncontinuous melt occurred as shown in Figures 22 and 23. No hardness profile was obtained on this material, due to the discontinuous appearance of the plasma sprayed layer after processing. However, localized hardness testing of the structure shown in Figure 22 showed a hardness of R_c 66 in the bulk of the WC 3015, and a hardness of R_c 75 in the gray areas.

Stellite No. 12

The processing of this material was performed with the system shown in Figure 2. The optimum processing parameters were determined to be 38.8 kW/in.^{2} (6000 W/cm^2) at a processing speed of 20 in./min (0.85 cm/^{2}) with a corresponding dwell time of 1.5 sec. At these parameters dense pore free deposits with thickness of 0.07 in. (0.178 cm) could be obtained. By overlapping consecutive runs, a continuous clad layer could be obtained as shown in Figure 24. The microstructure at the clad/substrate interface is shown in Figure 25, and the hardness profile of the cladded layer is shown in Figure 26. The hardness of the Stellite layer is, as expected, around Rockwell C 50. The slight drop at the interface shows that the dilution of the Stellite layer, by substrate melting, is very slight.

2.4 PROCESSING TEST SAMPLES

A total of 20 test samples were prepared for return to AMMRC. Each was prepared by making 5 to 8 individual laser runs (9 to 10 for the Stellite samples) in order to cover the entire surface area of each sample. The processing parameters used in the preparation of these samples are given in Table 3. Each sample was processed, as much as possible, at the optimum processing parameters, determined as described in Section 2.3 and listed in Table 4. However, evident variation in absorptivity among the samples of the same material required some variation in the processing parameters in order to obtain repeatable results as judged by surface appearance. This was particularly true for Specimens 9 and 10 (see Table 3).

No attempts were made to prepare specimens with molybdenum or WC 3015 surface layers, as the poor results obtained with these materials in the processing development phase did not justify further work with the equipment available.

Figure 21. Run No. 303 x 18
WC 3015: 432 kW/in.^{2} 50 in./min

K6800

Figure 22. Run No. 312 x 18
WC 3015: 280 kW/in.^{2} 50 in./min

K6799

Figure 23. Run No. 322 x 18
WC 3015: 156 kW/in.^{2} 25 in./min

Figure 24. Stellite No. 12 x 18
38.8 kW/in.^{2} 20 in./min

Figure 25. Stellite No. 12 x 180
38.8 kW/in.^{2} 20 in./min

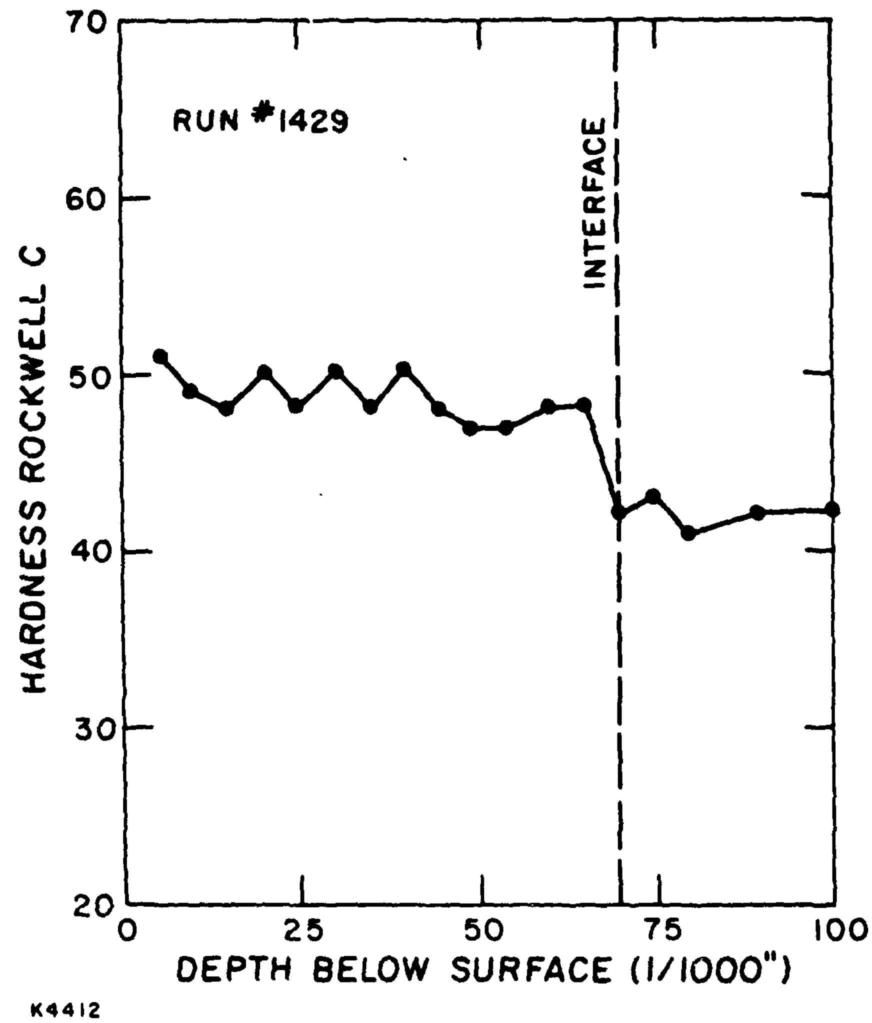

Figure 26. Hardness of Stellite No. 12 on SAE 4340 Steel Substrate

TABLE 3. PROCESSING OF TEST SPECIMENS

SPECIMEN #	MATERIAL	POWER DENSITY kW/in.^{2}	SPEED in./min	NUMBER OF INDIVIDUAL RUNS
1	Stellite #12 (Powder)	38.8	20	10
2	"	"	"	9
3	"	"	"	"
4	"	"	"	"
5	"	"	"	"
6	TA - 10W	194.5	16.8	8
7	"	194.0	16.6	6
8	"	194.0	16.0	6
9	TA	194.0	12.9	8
10	"	193.7	12.0	7
11	"	194	17.1	7

TABLE 3. PROCESSING OF TEST SPECIMENS (Continued)

SPECIMEN #	MATERIAL	POWER DENSITY kW/in.^{2}	SPEED in./min	NUMBER OF INDIVIDUAL RUNS
12	TA	194	17.4	7
13	"	194	17.4	7
14	WC 103	192	36.3	6
15	"	189.7	38	6
16	"	193	40.5	6
17	"	196	40.5	5
18	"	193	38	6
19	"	192.8	38	6
20	"	192.8	38	6

TABLE 4. SUMMARY OF PROCESSING PARAMETER STUDY

MATERIAL	POWER DENSITY ($kW/in.^2$)	PROCESSING SPEED (in./min)	DWELL TIME (sec)	OPTIMUM PARAMETERS
Mo	168 - 440	4 - 35	0.17 - 1.5	------------
Ta	168 - 440	6 - 40	0.15 - 1	194 $kW/in.^2$ at 16.8 in./min
Ta-10W	110 - 440	9 - 30	0.2 - 0.67	198 $kW/in.^2$ at 16.8 in./min
WC 103	272 - 440	10 - 45	0.13 - 0.6	187 $kW/in.^2$ at 34 in./min
WC 3015	156 - 440	20 - 70	0.09 - 0.3	--------------
STELLITE #12	32 - 38.8	5 - 25	1.2 - 6.0	38.8 $kW/in.^2$ at 20 in./min

3.0 SUMMARY AND CONCLUSION

The cladding of SAE 4340 steel with Stellite No. 12, yielded good results. Little dilution (inmelt into the substrate) good bonding and satisfactory hardness of the cladded layer were obtained. By overlapping adjacent individual laser runs by ~ 50 percent, it was possible to obtain a continuous clad layer over the entire 4 in. x 4 in. sample surface area.

The results of the laser processing of the refractory metals show that true laser cladding of steel substrates with these materials is very difficult to achieve, due to the reactivity of the materials and to the great difference in melting points between the cladding materials and the steel substrate. Considerable densification of the plasma sprayed refractory metal surface layers could be obtained (see Figures 7, 8 and 19), but attempts to melt the surface layers resulted in damage to the substrate or alloying between substrate material and the cladding material (Figures 15 and 17). Cracking and pore formation were also evident when melting of the plasma sprayed surface layer occurred.

Another problem encountered in the laser processing of the refractory materials, was contamination by oxygen and nitrogen from the processing atmosphere. This is shown by the high hardness of the processed materials.

In order to obtain more satisfactory results, improved processing techniques, in particular, an improved protective atmosphere must be used. It should then be possible to obtain better densification, and for the relative low melting alloys WC 103 and WC 3015, true cladding by melting may be possible.

4.0 RECOMMENDATION FOR FURTHER WORK

Further work in this area should be concentrated on materials with melting points that are < 1000°C higher than that of the steel substrate. Possible candidates are:

- WC 103, WC 3015 or similar alloys, laser processed under very good protective atmospheres. Densification of plasma sprayed layers should then prove possible. If the material is applied to the substrate surface in the form of loose powder, rather than by plasma spraying, it may also prove possible to obtain true cladding by melting, because in this case, absorptivity of the laser beam will be enhanced, while heat conduction to the substrate will be less than for a solid layer.

- A somewhat lower melting alloy, such as Cr-25 Fe-15 Mo[1] (MP ~ 1700°C) which could be laser cladded in the form of prealloyed powder, or surface alloyed with the substrate, using a Fe-lean starting material.

- Use hardfacing alloys with higher melting points than Stellite No. 6 or Stellite No. 12, followed by chrome plating. One candidate alloy that has been considered is Stellite No. 21[1] with a melting point of 1283°C. This alloy is sensitive to iron contamination, and laser cladding should, therefore be a good way to apply this material due to the low dilution obtainable by this technique. Other candidate alloys in this class are Wallex No. 6 (melting point 1395°C) and Colmonoy C-395, (melting point 1395°C) and Colmonoy C-395, (melting point 1480°C). This last alloy is particularly interesting in terms of laser processing because it cannot be cladded onto steel with conventional techniques. Furthermore, this is not a cobalt base alloy, thus negating the need for this scarce and expensive material. Table 5 lists the composition and properties of the alloys discussed above.

- Finally, the cladding of the gun barrel in the origin of rifling area with a material of high thermal conductivity, followed by chrome plating, may prove beneficial. If, for example, a 20 mil layer of nickel is used as an intermediate layer between the chrome-plating and steel, the maximum surface temperature experienced during firing may be lowered by as much as 160 to 200°C. The mechanical strength of nickel is not comparable to that of steel at room temperature, but at temperatures close to the melting point (1435°C for nickel), the difference in strength is much less.

TABLE 5. CANDIDATE ALLOYS FOR GUNTUBE CLADDING

Alloy	M.P. C°	Composition Weight Per Cent	Hardness Rockwell C
Stellite #21	1283	0.3C, 25-30Cr, 4.5-6.5Mo, 1.5-3.5Ni, 2(max)Fe, Bal Co	32
Wallex #6	1395	1C, 29Cr, 4.5W, 1.25Si, other 6.5, Bal Co.	39-44
Colmonoy C-395	1480	0.5C, 13Cr, 37Ni, 2.5Si 1.5B, FE Bal.	35-45
CR-25Fe-15Mo	~1700	65Cr, 25Fe, 15Mo	--

5.0 APPENDIX

5.1 HEAT FLOW CALCULATIONS

In theory, the most suitable laser processing parameters for the plasma sprayed specimens could be determined by heat flow analysis, but in practice, this is difficult for the following reasons:

1. The actual power absorbed by the specimen is unknown and varies from specimen to specimen.

2. When melting occurs, the heat flow problem becomes nonlinear, and no exact analytical solution exists for this case. Onset of evaporation further complicates this problem.

3. The thermal properties of the materials continuously change with the temperature.

Still, it is possible to obtain a qualitative picture of the process by assuming that the molten phase has similar thermal properties to that of the solid, neglecting the heat of fusion and using an average value for thermal conductivity and thermal diffusivity, defines as:

$$K_{av} = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} K\,(T)\,dT$$

$$\alpha_{av} = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} \alpha\,(T)\,dT$$

By using published data for the values of these quantities at various temperatures and performing numerical integration, the averages can thus be calculated.

The heat flow in a composite body can be evaluated from the expressions[4,5]

$$T_1 = \frac{2Fo}{K_1}\sqrt{\alpha_1 t} \sum_{N=-\infty}^{\infty} \varepsilon^{|N|} \, \mathrm{ierfc}\left[\frac{|Z - 2n\ell|}{2\sqrt{\alpha_1 t}}\right] \quad \left(Z \overline{<} \ell\right)$$

$$T_2 = \frac{2Fo}{K_2}\sqrt{\alpha_2 t} \sum_{M=0}^{\infty} \varepsilon^{M} \, \mathrm{ierfc}\left(\frac{Z - \ell}{2\sqrt{\alpha_2 t}} + \frac{(2m+1)\ell}{2\sqrt{\alpha_1 t}}\right) \quad \left(Z \overline{>} \ell\right)$$

where

K_1	=	Thermal conductivity of the surface layer
K_2	=	Thermal conductivity of substrate
α_1	=	Thermal diffusivity of the surface layer
α_2	=	Thermal diffusivity of substrate
Q	=	Laser power density
t	=	Dwell time
Z	=	Depth below the surface
ℓ	=	Thickness of surface layer
T_1	=	Temperature in surface layer
T_2	=	Temperature in substrate
ε	=	$K_1 \sqrt{\alpha_2} - K_2 \sqrt{\alpha_1}/K_1 \sqrt{\alpha_2} + K_2 \sqrt{\alpha_1}$

Utilizing these expressions for the composite TA/4340, and using published data[6] to determine the average values of the thermal properties, the temperature profiles for three different laser processing conditions were calculated. The results are shown in Figure 27.

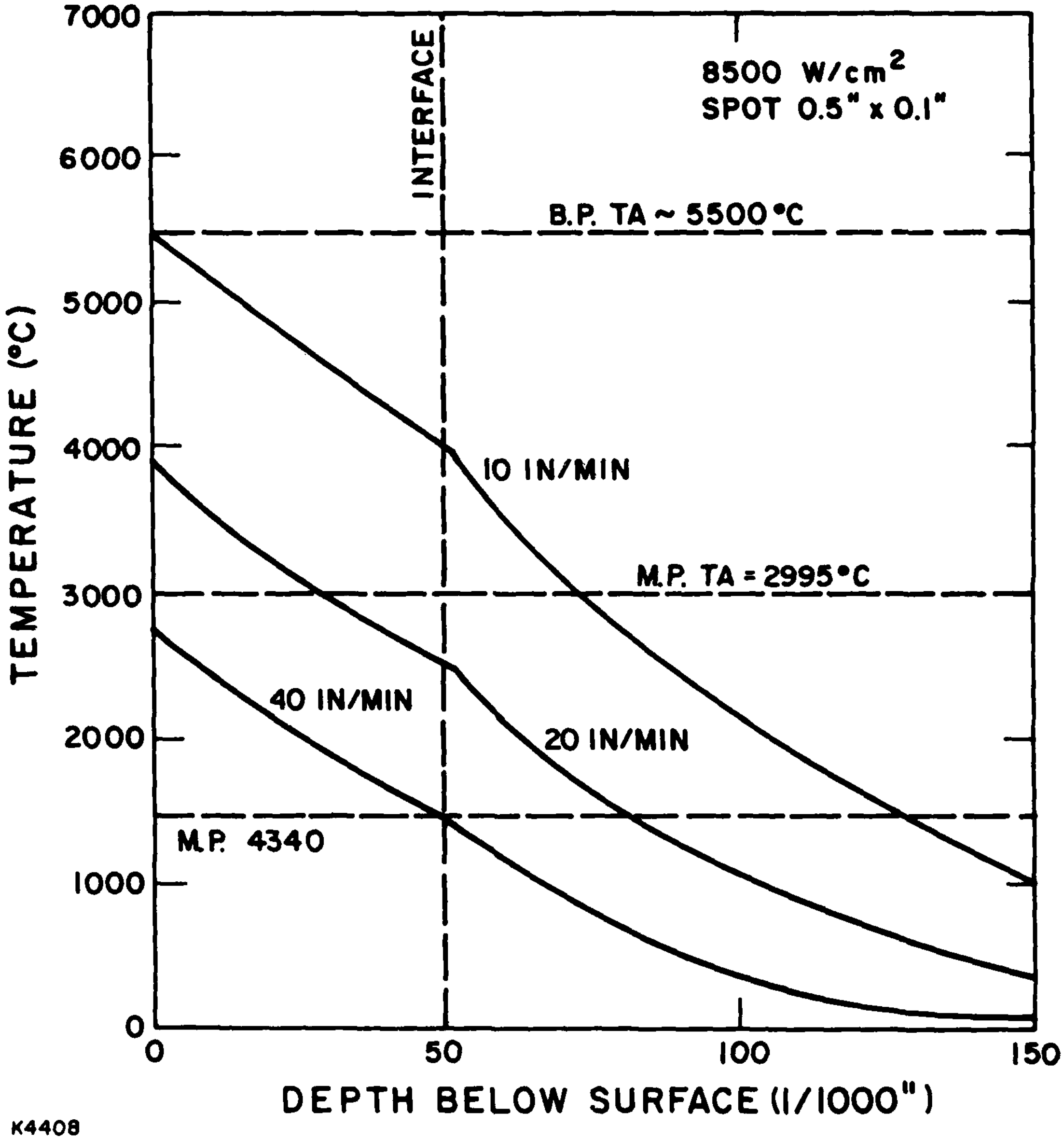

Figure 27. Temperature Profiles in Ta-SAL 4340 Steel Composite

It is apparent from these results that only a small fraction of the laser energy was actually absorbed into the workpiece, because the power density used in these calculations is only 10 to 30 percent of the power densities actually used. Furthermore, it is clear that melting of the surface layer down to the substrate interface is not possible without severe damage to the substrate.

If the surface layer is in the form of loose powder prior to laser processing the condition may be less severe because absorption of laser energy is likely to be higher, while heat conduction to the substrate will be reduced.

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Illus.-tables, Contract DAAG80-C-0044
D/A Project: 1L1612105AH84
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Final Report, January 1980 to March 1982

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Lasers

This program investigated the feasibility of surface melting and densification of plasma sprayed refractory metal coatings of SAE 4340 steel by means of a 15 kW CO_2 laser. The refractory metals and alloys investigated were: Tantalum, TA-10W, Molybdenum and the Columbium base alloys WC 103 and WC 3015.

True cladding, by melting of the plasma sprayed coatings, could not be achieved without damage to the substrate, or without alloying with the substrate. Partial melting or densification could be obtained, but pore formation and contamination by oxygen and nitrogen from the ambient atmosphere occurred in nearly all cases. It may, however, be possible to overcome these problems by improving the protective atmosphere used for the processing; and by laser processing the refractory metals in the form of loose powder on the substrate surface rather than as a plasma sprayed layer.

Cladding of SAE 4340 steel with Stellite No. 12 was also investigated. Good, fully dense continuous layers, ~0.07 in. thick, with a hardness of R_c 48-50, were obtained.

DAT
FILM